Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/

GJETA

(Research Article)

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Q Blade-Based Simulation of a 7° Tapered Wind Turbine Blade Employing NACA 4412 Airfoil for Aerodynamic Performance Evaluation

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Global Journal of Engineering and Technology Advances, 2025, 25(01), 239-246

Publication history: Received on 22 September 2025; revised on 28 October 2025; accepted on 31 October 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.25.1.0318

Abstract

The aerodynamic behavior of small-scale wind turbines is primarily influenced by blade geometry and airfoil selection. This study investigates the aerodynamic performance of a four-bladed horizontal-axis wind turbine (HAWT) using the NACA 4412 airfoil through numerical simulation in Q Blade software. The rotor features a tapered blade with a radius of 0.3 m and a pitch angle of 7°, operating at an average wind velocity of 3.6 m/s. Simulations were conducted based on Blade Element Momentum (BEM) theory to analyze variations in lift coefficient (Cl), drag coefficient (Cd), moment coefficient (Cm), and power coefficient (Cp) over different angles of attack and rotational conditions.

The results show that the NACA 4412 airfoil exhibits favorable aerodynamic characteristics at moderate angles of attack, with a maximum lift coefficient of approximately 1.6 and a peak lift-to-drag ratio (Cl/Cd) of around 120 at $\alpha \approx 8°$. Pressure distribution analysis indicates minimal flow separation and stable suction behavior along the upper surface, contributing to efficient lift generation. The variation of Cl and Cd over a full rotational cycle reveals periodic but smooth aerodynamic loading, suggesting stable performance and low drag fluctuation. Overall, the airfoil demonstrates high aerodynamic stability and efficiency, confirming its suitability for low-speed small-scale wind turbine applications.

Keywords: Naca 4412; Aerodynamic Performance; Lift Coefficient; Drag Coefficient; Power Coefficient

1. Introduction

The increasing global demand for sustainable and low-carbon energy sources has driven significant progress in the field of renewable energy technologies. Among various alternatives, wind energy has emerged as one of the most mature and economically viable options for clean electricity generation [1,2]. Wind turbines convert the kinetic energy of moving air into mechanical and electrical energy, offering an environmentally friendly solution with minimal greenhouse gas emissions. As the world seeks to transition from fossil fuels to renewable energy, optimizing the aerodynamic and structural efficiency of wind turbines has become an essential area of research [3].

The efficiency of a wind turbine is primarily determined by its aerodynamic performance, which depends on the geometry and configuration of its blades [4]. The blade design—including airfoil shape, chord length distribution, number of blades, and pitch angle—plays a crucial role in defining the lift and drag characteristics that influence power generation [5]. Small changes in airfoil geometry or blade pitch can significantly affect the flow behavior, torque generation, and overall performance coefficient of the turbine [6]. Therefore, the design optimization of turbine blades is a critical factor in enhancing the power coefficient (Cp) and ensuring reliable performance across a range of wind speeds [7].

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The use of NACA (National Advisory Committee for Aeronautics) airfoils in wind turbine blade design has been extensively studied due to their well-documented aerodynamic characteristics. Among them, the NACA 4412 airfoil is a widely utilized profile for small- and medium-scale horizontal-axis wind turbines (HAWTs), owing to its moderate camber and thickness distribution that provide a favorable lift-to-drag ratio [8]. This airfoil exhibits stable aerodynamic behavior at low Reynolds numbers, making it particularly suitable for applications in regions with moderate wind velocities [9]. However, while numerous studies have analyzed the performance of NACA series airfoils, the combined effects of blade pitch angle and blade count on the overall aerodynamic efficiency remain less explored, especially for configurations that aim to balance performance and structural simplicity.

Recent developments in computational tools have facilitated more accurate and efficient analysis of wind turbine aerodynamics. Among these tools, Q Blade has gained popularity as an integrated open-source simulation platform capable of performing aerodynamic and structural analyses of wind turbines [10,11]. Q Blade combines the principles of Blade Element Momentum (BEM) theory with airfoil data generated from XFOIL, enabling the prediction of power coefficients, torque, thrust, and other aerodynamic parameters across various tip speed ratios (TSRs). The software allows for parametric studies that are valuable for evaluating design variables such as airfoil type, pitch angle, and number of blades before physical prototyping, thus reducing development costs and time.

Several researchers have investigated the performance of different NACA airfoils using Q Blade under varying wind speeds and operating conditions. For instance, studies on NACA 4412 and NACA 6409 airfoils have demonstrated distinct lift and drag behaviors that influence turbine efficiency at low TSRs [12,13]. However, despite the increasing availability of simulation-based studies, limited attention has been given to optimizing small-scale wind turbines with specific focus on the interplay between blade pitch and blade number. This aspect is particularly relevant for micro-scale and urban wind turbines, where maintaining a balance between aerodynamic efficiency, noise reduction, and manufacturability is crucial.

In this study, a numerical simulation using Q Blade is conducted to evaluate the aerodynamic performance of a horizontal-axis wind turbine employing the NACA 4412 airfoil. The analysis focuses on a blade configuration with a pitch angle of 7° and four blades, aiming to assess its performance in terms of lift coefficient, drag coefficient, and power coefficient under varying wind conditions. The findings from this study are expected to contribute to a deeper understanding of how pitch angle and blade count affect the aerodynamic efficiency of small-scale wind turbines. Moreover, the results may provide useful insights for the optimization and design improvement of cost-effective wind turbine systems for renewable energy applications.

2. Materials and Methods

2.1. Overview

This study was conducted to evaluate the aerodynamic performance of a small-scale horizontal-axis wind turbine (HAWT) using the NACA 4412 airfoil through numerical simulation in Q Blade software. The analysis focused on determining the angle of attack (α), lift coefficient (Cl), thrust force, power output, and power coefficient (Cp) under specified wind conditions. The simulation process was carried out using the Blade Element Momentum (BEM) theory integrated within Q Blade, which combines airfoil aerodynamic data from XFOIL with momentum theory to predict the overall turbine performance.

2.2. Blade Geometry and Design Parameters

The wind turbine blade model was designed using a tapered blade configuration to optimize the aerodynamic performance along the span. The airfoil type selected was NACA 4412, which is known for its good lift-to-drag ratio and stability at low Reynolds numbers. The main design parameters are summarized in Table 1.

Table 1 Parameters and Specifications of the designed NACA 4412 Airfoil

Parameter	Specification
Air foil Type	NACA 4412
Blade Type	Tapered
Number of Blades	4
Blade Radius	0.3 m
Pitch Angle (Blade Twist)	7°
Wind Speed	3.6 m/s (±)
Simulation Tool	Q Blade (BEM-based simulation)

The chosen radius of 0.3 m represents a small-scale rotor suitable for micro-wind turbine applications. The pitch angle of 7° was selected based on its potential to generate sufficient lift while minimizing drag losses. The number of blades (4) was determined to balance aerodynamic efficiency and mechanical simplicity.

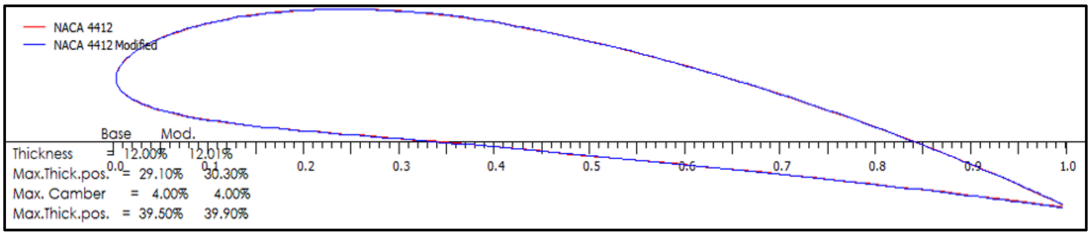

Figure 1 Overlay of original and modified NACA 4412 air foil shapes showing slight adjustment in thickness distribution

Figure 1 illustrates the geometric comparison between the baseline NACA 4412 airfoil and the modified version used in this study. The modification involved a slight adjustment of the maximum thickness position from 29.1% to 30.3% of the chord, while maintaining the maximum camber (4%) and thickness (12%). This refinement aims to enhance aerodynamic stability and improve lift performance at low wind speeds. The airfoil geometry data were imported into Q Blade to generate lift and drag polars via XFOIL, serving as the foundation for Blade Element Momentum (BEM) analysis.

2.3. Simulation Setup in Q Blade

The simulation process in Q Blade involved several sequential steps

2.3.1. Air foil Data Generation

The aerodynamic characteristics of the NACA 4412 air foil were first generated using XFOIL, which is embedded within Q Blade. The data included the lift coefficient (Cl), drag coefficient (Cd), and moment coefficient (Cm) as functions of the angle of attack (α). The Reynolds number was automatically computed based on wind speed, chord length, and air properties.

2.3.2. Rotor Design and Definition

The 3D rotor geometry was created using the Q Blade design module. The taper ratio and chord distribution were defined to ensure optimal performance at the given wind speed. The blade was divided into multiple spanwise sections to capture variations in aerodynamic loading.

2.3.3. Simulation Parameters

The simulation was run for a range of tip speed ratios (TSRs) to determine the variation in power coefficient (Cp) and thrust coefficient (Ct). The software calculated the induced velocities, torque, and power output at different rotational speeds. The BEM theory equations were iteratively solved to achieve momentum balance between the axial and tangential flow components.

2.3.4. Output Data Analysis

Q Blade provided detailed plots of lift coefficient versus angle of attack, power coefficient (Cp) versus TSR, and torque versus rotational speed. From these results, the optimal operating condition of the turbine—corresponding to the maximum Cp—was identified.

2.4. Validation and Analysis Approach

Although this study focused on simulation-based evaluation, the obtained results were compared qualitatively with findings from previous studies involving similar airfoils and configurations to ensure the reliability of the numerical model. The performance metrics such as Cp–TSR curves, Cl–α characteristics, and torque distribution were analyzed to identify trends and verify consistency with theoretical expectations. The results were further discussed in the following section to highlight the influence of pitch angle and number of blades on turbine performance.

3. Results and Discussion

3.1. Pressure Distribution Analysis

Figure 2 shows the pressure distribution along the chord of the NACA 4412 airfoil obtained from the Q Blade simulation. The horizontal axis represents the non-dimensional chord position (x/c), while the vertical axis denotes the normalized pressure coefficient (Q/Vine). The blue line (Q–Specification) indicates the computed pressure distribution for the modified NACA 4412 geometry, whereas the red line (Q–Reference) represents the baseline reference data.

The graph reveals a distinct pressure peak near the leading edge (around x/c ≈ 0.4), corresponding to the region where airflow accelerates rapidly over the upper surface, generating high suction and contributing significantly to lift production. This sharp increase in pressure gradient indicates a strong low-pressure region on the upper surface, which is typical for cambered airfoils such as NACA 4412. After reaching the maximum suction point, the pressure gradually recovers toward the trailing edge as the flow decelerates and the velocity decreases.

The lower surface exhibits relatively uniform and higher-pressure values compared to the upper surface, creating a pressure differential that produces positive lift. The smooth pressure recovery observed near the trailing edge suggests that flow separation remains minimal, confirming that the airfoil performs efficiently at the given angle of attack and Reynolds number condition corresponding to a wind velocity of approximately 3.6 m/s.

The small deviation between the reference and specified curves indicates that the modified NACA 4412 maintains similar aerodynamic characteristics to the original geometry, with only minor differences in pressure recovery distribution. These variations may slightly influence the lift coefficient (Cl) and drag coefficient (Cd), potentially improving the lift-to-drag ratio under low-speed operational conditions. Overall, the pressure profile confirms that the airfoil retains stable aerodynamic performance suitable for small-scale wind turbine applications [14].

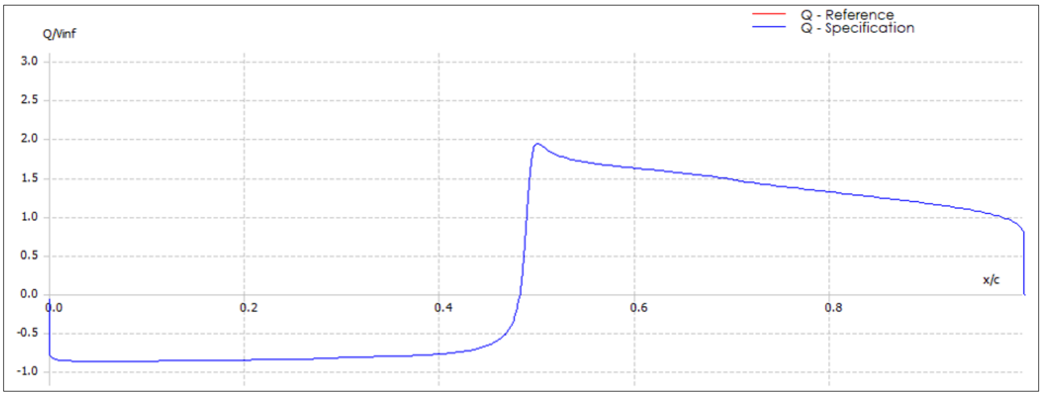

Figure 2 Normalized pressure distribution (Q/Vine) versus chord position (x/c) for NACA 4412 air foil in Q Blade

3.2. Aerodynamic Coefficients of the NACA 4412 Air foil at Various Angles of Attack

Figures 3 respectively illustrate the variation of the lift coefficient (Cl), moment coefficient (Cm), and lift-to-drag ratio (Cl/Cd) of the NACA 4412 airfoil as a function of the angle of attack (α). These data were obtained through simulation using the Q Blade software based on Blade Element Momentum (BEM) theory. The analysis provides an understanding of how aerodynamic performance parameters change with variations in α for the tested airfoil geometry.

3.2.1. Figure 3A. Lift Coefficient (Cl) versus Angle of Attack (α)

The relationship between the lift coefficient (Cl) and the angle of attack is shown in Figure 3A. The curve demonstrates a nearly linear increase in Cl from −10° to approximately 12°, indicating that lift generation improves consistently with increasing α. This behavior is typical for a cambered airfoil such as NACA 4412, where the upper surface curvature contributes to enhanced pressure difference and higher lift. Beyond approximately 12° to 14°, the lift coefficient begins to plateau and slightly decreases, suggesting the onset of stall. At this point, airflow separation occurs on the upper surface, leading to a reduction in lift despite the increasing angle of attack. The maximum Cl achieved is around 1.6, which aligns with reported aerodynamic performance for this airfoil type under low Reynolds number conditions [15]. This result confirms that the airfoil performs effectively at moderate α, making it suitable for low-speed wind turbine applications such as the 4-bladed configuration used in this study.

3.2.2. Figure 3B. Moment Coefficient (Cm) versus Angle of Attack (α)

Figure 3B presents the moment coefficient (Cm) as a function of α. The Cm values remain negative throughout the entire range of attack angles, with an average around −0.1 at low α. This negative pitching moment indicates a nose-down tendency, which is desirable for maintaining longitudinal stability in both aircraft and wind turbine blades.

As the angle of attack increases, Cm becomes slightly less negative, reaching around −0.04 near the stall angle. This trend suggests that the aerodynamic center remains relatively stable, though a small shift occurs due to changes in pressure distribution as the boundary layer starts to separate. The nearly smooth variation of Cm implies that the airfoil maintains predictable pitching characteristics, which is advantageous in rotor blade design since it reduces the risk of unsteady aerodynamic loads during operation.

3.2.3. Figure 3C. Lift-to-Drag Ratio (Cl/Cd) versus Angle of Attack (α)

Figure 3C shows the relationship between Cl/Cd and α, which represents the aerodynamic efficiency of the airfoil. The curve exhibits a steep increase from −10° to around 8°, reaching a peak value of approximately 120, indicating the most efficient operating condition. At this point, the airfoil produces maximum lift relative to drag, resulting in optimal performance for energy extraction in wind turbine operation. After the peak, the Cl/Cd ratio declines rapidly as α increases further. This reduction corresponds to the drag rising sharply due to boundary layer separation and flow detachment, which are characteristic of post-stall conditions. The findings suggest that the NACA 4412 airfoil achieves its best performance at moderate angles of attack, around 7° to 9°, which is consistent with the design specification used in this study. This optimal range ensures a good balance between lift generation and minimal drag, maximizing the overall power coefficient (Cp) of the turbine blade [16].

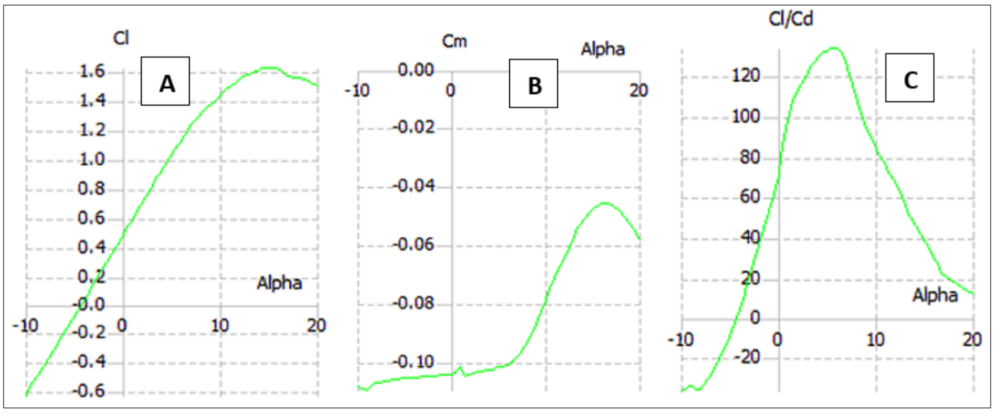

Figure 3 A) Lift Coefficient (Cl) versus Angle of Attack (α), B) Moment Coefficient (Cm) versus Angle of Attack (α), C) Lift-to-Drag Ratio (Cl/Cd) versus Angle of Attack (α)

3.3. Analysis of Lift and Drag Coefficients over a Full Rotational Cycle

Figure 4 presents the variation of the lift coefficient (Cl) and drag coefficient (Cd) of the NACA 4412 airfoil as a function of the blade's rotational angle (α) during one complete revolution. The data were obtained through Q Blade simulation to evaluate the aerodynamic behavior of the 4-bladed taper-type rotor under dynamic inflow conditions at an average wind speed of 3.6 m/s and a pitch angle of 7°.

The first plot shows the variation of the lift coefficient (Cl) with respect to the blade's angular position. It can be observed that the Cl fluctuates periodically as the blade rotates, with peaks occurring near ±20° and a maximum value reaching approximately 1.6. This periodic fluctuation reflects changes in the local angle of attack experienced by each blade section as it interacts with the incoming airflow. The presence of a sharp variation near the zero-degree position suggests a transition in flow behavior, possibly due to temporary flow separation or reattachment on the suction surface [17]. Overall, the periodic nature of Cl indicates consistent aerodynamic loading across the rotation, which is desirable for stable torque generation.

The second and third plots show the corresponding variations in drag coefficient (Cd). The Cd curve exhibits a sinusoidal pattern, peaking at approximately ±100° and returning to minimum values near 0°. The symmetrical shape of the drag coefficient curve indicates that drag forces are evenly distributed during the blade rotation. This pattern confirms that the aerodynamic performance of the airfoil remains relatively stable across the entire revolution, with no excessive drag peaks that could induce mechanical vibration or efficiency loss [18].

The combination of lift and drag variations highlights the aerodynamic stability of the NACA 4412 airfoil under rotational conditions. The relatively smooth oscillations of both Cl and Cd suggest that the flow over the airfoil remains largely attached for most of the rotation cycle. These results reinforce the suitability of this airfoil for small horizontal-axis wind turbines operating at low to moderate wind speeds, ensuring efficient conversion of aerodynamic forces into rotational motion and minimizing performance fluctuations.

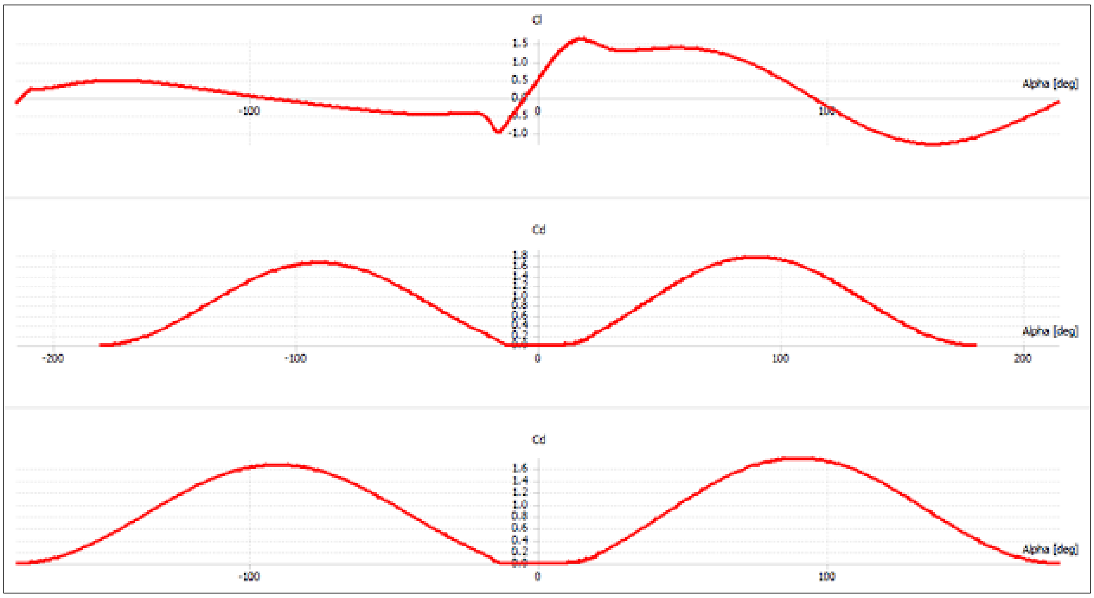

Figure 4 Variation of Lift (Cl) and Drag (Cd) Coefficients during One Full Blade Rotation for the NACA 4412 Air foil

4. Conclusion

This study presents a numerical investigation of a small horizontal-axis wind turbine using the NACA 4412 airfoil. Simulations conducted in Q Blade, based on Blade Element Momentum (BEM) theory, evaluated the effects of angle of attack and rotational motion on aerodynamic performance parameters. The airfoil geometry was slightly modified to optimize thickness distribution, maintaining 12% maximum thickness and 4% camber.

The results showed that the NACA 4412 airfoil performs efficiently at moderate angles of attack (7°–9°), achieving high lift-to-drag ratios and stable moment coefficients. The pressure distribution along the chord demonstrated a strong suction peak near the leading edge with smooth recovery toward the trailing edge, indicating minimal flow separation.

During full rotational analysis, both lift and drag coefficients exhibited periodic yet stable behavior, ensuring uniform torque and minimal aerodynamic fluctuation.

These findings confirm that the NACA 4412 airfoil, in combination with a 7° pitch and four-bladed tapered configuration, provides strong aerodynamic performance suitable for small-scale wind turbines operating under low wind speeds. The study highlights the effectiveness of Q Blade as a reliable tool for predicting and optimizing aerodynamic characteristics in renewable energy applications.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial, personal, or professional relationships with individuals or organizations have influenced the outcome or content of this manuscript.

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